Modelling the effect of sand extraction on the Kwinte Bank

Dries Van den Eynde[1] & Alain Norro

Management Unit of the North Sea Mathematical Models
Belgian Royal Institute of Natural Sciences
Gulledelle 100, B-1200 Brussels, Belgium

Abstract

In recent years, the exploitation of marine aggregates is increasing. In Belgium coastal waters, especially the Kwinte Bank is under severe pressure. During the last decade, a “depression” of 5 m developed, due to extraction of sand. Norro *et al.* (2003; 2006; 2009) and Norro and Ozer (2006) showed that during the period 1991-1998 the volume of the sand bank decreased significantly. In the present paper, the influence of these bathymetric changes on the sedimentation and deposition patterns are studied by numerical modelling, to obtain a first impression of the ability of the sand bank to recuperate from this sand extraction.

A three-dimensional hydrodynamic model, a wave model and a local total load sediment transport model are presented, which are used to investigate the sedimentation and deposition patterns. The hydrodynamic model results are validated using ADCP current data, showing that the model gives satisfactory results, while the wave model is used for operational forecasts of the waves at the Belgian coast, thus being validated continuously. The sediment transport model results are much more subject to uncertainties but the results are in general agreement with observations.

The numerical model results show that apart from the extraction of marine aggregates, the Kwinte Bank also is subject to a natural erosion of the top of the sand bank. The predicted erosion of the sand bank is of the same order of magnitude as the difference between the calculated volumetric decrease of the top of the sand bank and the estimated amount of extracted aggregates. This natural erosion of the Flemish sand banks was also found by De Moor (2002).

The study therefore seems to confirm that the sand bank is not recuperating from the extraction of sand, but that by natural processes, the sand bank is further being eroded. This clearly raises the question of the sustainability with regard to the extraction of marine aggregates and suggests that the authority should define maximum exploitable quota preventing any irreversible damage.

Keywords: Sand bank, sand extraction, morphologic evolution, numerical modelling, Southern North Sea

1. Introduction

The demand for marine sand in Europe is increasing. In 2004, Europe produced around 53 million m³ sand and gravel of marine origin (ICES, 2005). Since 1980, the winning of marine aggregates in water under the Belgian jurisdiction has almost quadrupled to almost 3 million ton (or 1.9 million m³) each year. Most of the extraction is executed in two large exploitation zones, the first one around the Thornton

[1] Corresponding author. Tel. + 32 2 773 21 30; fax: + 32 2 770 69 72; e-mail: D.VandenEynde@mumm.ac.be

Bank and the Goote Bank, the second one around the Kwinte Bank, Buitenratel and Oostdyck (Figure 1). Until recently, more than 80 % of the extraction took place on the Kwinte Bank, especially a small part in the Northwest and central part of the sandbank was used. This has resulted in the formation of a depression lying about 5 m below the original sea floor, about 700 m wide and 1 km long, the so-called Central Depression (Degrendele *et al.*, 2002).

The effects of the extraction of marine aggregates are not fully known. The extraction has changed the form, the volume and the height of the sand bank significantly. This altered morphology, however, can also have influences on current and wave patterns in the coastal waters, with possible implications on, *e.g.*, the erosion of the coasts (Van Lancker *et al.*, 2009b). Further also the biological impact of the extraction of sand on the pelagic fauna is clear (Van Lancker *et al.*, 2009b). To permit the study of the possible effects of extraction of the sand bank, the depression zone was closed for exploitation by the Government in February 2003, for at least six years. The objective was to set up reliable practical criteria for the maximum quantity of sand that can be extracted without altering the long-term stability of the bank.

Norro *et al.* (2006) and Norro and Ozer (2006) used bathymetric profiles which were taken over the period 1988-1999 to study the volumetric decline in the Kwinte Bank. They showed that there was a significant decrease in the volume of the top of the Kwinte Bank, which exceeded the estimated exploited volume in the same period. The fact that the estimated volumetric decline in the bank is larger than the estimated workload raised the question whether the activity on the sandbank has perturbated the dynamic equilibrium of the bank.

In Van den Eynde *et al.* (2009) numerical models were used to study the influence of the sand extraction on the sand transport and the stability of the sand bank. Three different scenarios were investigated, related to the amount and intensity of the dredging. The results show that the sand extraction does not appear to affect the stability of the bank.

In this paper the question is addressed from a different point of view. The numerical model for the sand transport on the sand bank, which was set up in Van den Eynde *et al.* (2009), is used on the different bathymetries, which were constructed from the bathymetric profiles. For each of the different bathymetries, the erosion and deposition were calculated and the evolution of the erosion and deposition was followed. This temporal evolution could again give an indication whether the dynamic balance of the bank was disturbed.

The paper is organized as follows. In a first section, the hydrodynamics and sedimentology of the Belgian Continental Shelf (BCS) and more specifically the Kwinte Bank are discussed. The numerical models are briefly discussed in the next section. Some results of the numerical models are compared with measurements in the area. In the core of the paper, the results of the numerical models for the different bathymetries of the Kwinte Bank are discussed. Some conclusions are formulated in the last section.

2. Hydrodynamics and sedimentology of the Kwinte Bank

The Kwinte Bank is one of the Flemish Banks, located in the southern Bight of the North Sea (Figure 1).

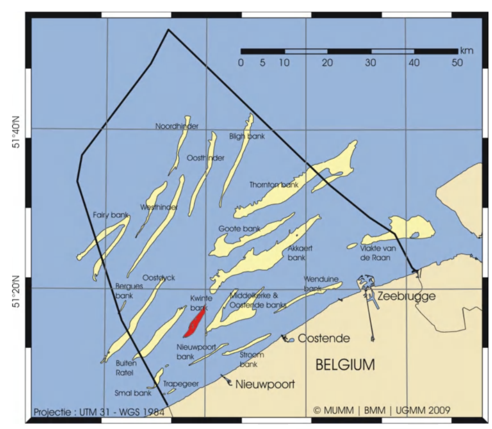

Figure 1: Location of the Kwinte Bank on the Belgian Continental Shelf.

The bank is a tidal current ridge of the North Sea Belgian coast and is oriented at a SW-NE direction. The Kwinte Bank is characterized by a length of about 15 km, with a width varying from 2 km in the southern part to 1 km in the northern part (Figure 2). The minimum water depth is close to 5 m. In the northern part and the middle part of the sand bank, large dunes are found, with a maximum amplitude of about 6 m. On top of the sand dunes, mega ripples are present. The cross-section of the bank is clearly asymmetrical with the steeper side facing the northwest.

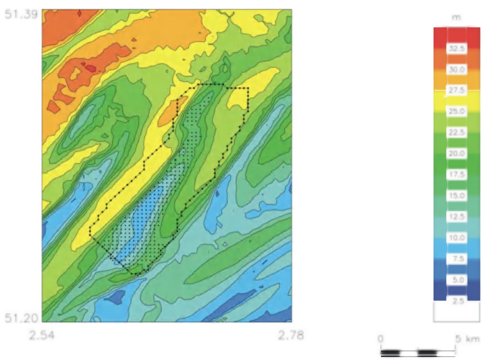

Figure 2: Detailed bathymetry of the Kwinte Bank, bathymetry *Jun-1998*. The dots indicate the area, which is considered as the top of the bank, with a depth less then 15 m below MLLWS.

The current ellipses in the Kwinte Bank region (Figure 3) are typically varying depending on their location, *i.e.*, in the swale or on the sand bank. The ellipses are more spherical on the sand banks than in the deeper swales between the sand banks.

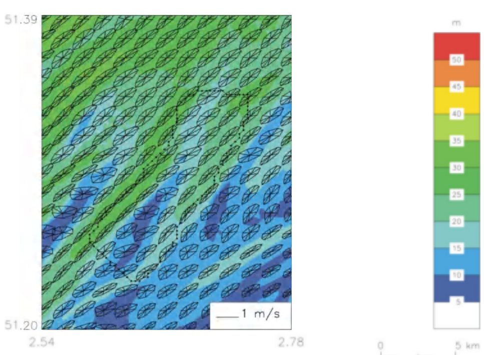

Figure 3: Current ellipses on the Kwinte Bank.

In the swales, the major axes of the ellipses are nearly in the same direction as the swale/sand bank axis, whereas on the sand bank the major ellipse axes are rotated clockwise compared to the bank axis. The maximum currents are around 0.8 to 0.9 m/s on the Kwinte Bank during spring tide and around 0.4 to 0.5 m/s during neap tide.

The Kwinte Bank is characterized by fine to medium-size sand (Figure 4). In the southern part of the bank, sand is found with a median grain size D_{50} of 180 to 240 µm, while in the middle and the northern part of the bank, coarser material can be found, with a median grain size up to about 400 µm.

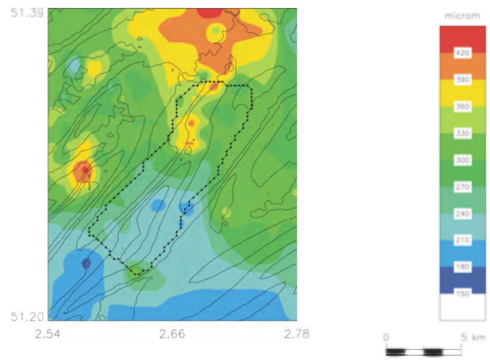

Figure 4: Median grain size of the Kwinte Bank.

3. Numerical models

3.1. Hydrodynamic model

The three-dimensional hydrodynamic model COHERENS (Luyten *et al.*, 1999) calculates the currents and the water elevations under the influence of the tides and the atmospheric conditions. This model has been developed between 1990 and 1998 in the framework of the EU projects PROFILE, NOMADS and COHERENS. The hydrodynamic model solves the momentum equation, the continuity equation and the equations of temperature and salinity. The equations of momentum and continuity are solved using the 'mode-splitting' technique. COHERENS disposes of different turbulence schemes, including the two equation *k-ε* turbulence model. A good description of turbulence is important when simulating the vertical current profile.

The model is implemented on two model grids for the BCS. The coarse grid model BCS has a resolution of 42.86" in longitude (817 – 833 m) and of 25" in latitude (772 m). The resolution of the fine model BCS-F is three times better. The extension of both models is indicated in Figure 5. On the open sea boundaries, the models are coupled with two regional models. The CSM model comprises the Northwest

European Continental Shelf and calculates the boundary conditions for the North Sea model (NOS). The NOS model generates the boundary conditions for the BCS model. The CSM model runs in two dimensions and is driven by the elevation at the open boundaries, governed by four semi-diurnal and four diurnal harmonic constituents.

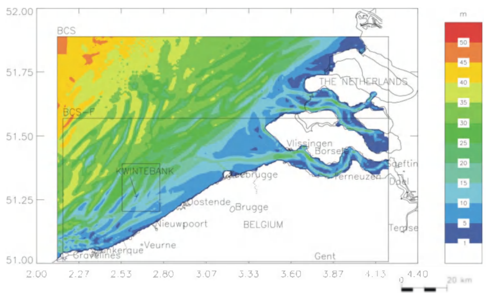

Figure 5: Bathymetry of the Belgian coastal waters. The large rectangle indicates the extension of the coarse BCS model grid, the smaller rectangle the extension of the fine BCS-F model grid. The smallest rectangle indication of the location of the Kwinte Bank and the extension of the grid where the Kwinte Bank results are shown.

The BCS model was extensively validated using about 400 hours of current profiles, which have been collected in the Belgian coastal zone, using a bottom mounted Acoustic Doppler Current Profiler (ADCP), type Sentinel 1200 kHz Workhouse from RDInstruments (Pison and Ozer, 2003; Van Lancker *et al.*, 2004). Statistical calculations (root-mean-square-error (RMSE), bias, correlation) have been carried out in order to apprehend the differences in norm and direction of the currents between model simulation results and ADCP measurement data. The RMSE of the amplitude of the currents is situated between 0.05 and 0.15 m/s, except for one campaign, while the error varies relative little with depth. Concerning the current direction, an error smaller than 10 % is found for most of the campaigns. The validation exercise therefore leads to the conclusion that the norm and the direction of the current profiles are satisfactory represented by the three-dimensional hydrodynamic model.

Two additional measuring campaigns with the ADCP were executed on the Kwinte Bank itself. The modelled and measured depth-averaged current velocity for the measuring campaign in March 2004 is presented in Figure 6. The calculated RMSE is 7.2 cm/s.

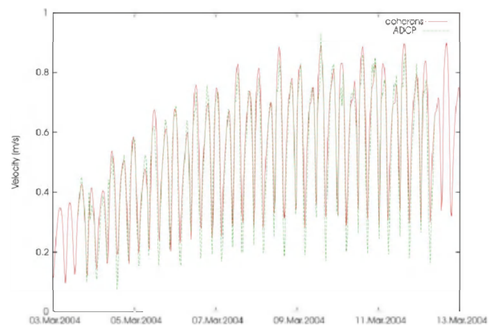

Figure 6: Measured and modeled (BCS-F) depth-averaged currents for a measuring campaign in March 2004 at station 2°40.245' E, 51°18.151' N.

3.2. Wave model

The waves are calculated with the MU-WAVE model (Van den Eynde, 1992). The core of the model is formed by the second generation HYPAS wave model (Günther and Rosenthal, 1985). This hybrid model combines the independent calculation of swell energy for each frequency and direction through a ray technique, with a parametrical wind sea model, using the JONSWAP parameters and the mean wind sea direction as prognostic variables. For the current application, the model is implemented on two nested stereographical grids. The North Sea grid has a resolution of 50 km × 50 km, whereas for the Southern Bight a resolution of 5 km × 5 km is implemented.

The MU-WAVE model has been tested extensively and is used in operational mode for the prediction of the waves at the BCS. Results of the first validation were presented in Van den Eynde (1992). The RMSE of the significant wave height on the BCS was 0.35 m, which gives a Scatter Index (*i.e.*, the ratio between the RMSE and the mean of the significant wave height) of 31.8 %. During later validations of the MU-WAVE model the results were compared with ERS-1 data, with buoy data and with results of the third generation wave model WAM (Ovidio *et al.*, 1994; Bidlot *et al.*, 1995). For the entire North Sea, a Scatter Index of 38 % was found for the significant wave height results, while in the Southern North Sea, the Scatter Index was 27 %. Taking into account the uncertainty in the wind field forecasts, these results are very satisfactory.

3.3. Sediment transport model

The sediment transport model MU-SEDIM is implemented on the same grid as the hydrodynamic model and calculates the total load under the influence of the local hydrodynamic conditions. Although more complicated models are available in literature, it was chosen to apply a simple total load formulae to model the sediment transport, since it was expected in this sandy environment that the sediment transport will be mainly as bedload, where an empirical formulae has to be used anyway.

From the different formulae available in literature, the formulae of Ackers-White (1973) was chosen, which gave the best results in a comparison, carried out by Sleath (1984). The bottom stress, one of the most important driving forces, is a function of the depth-averaged current velocity and of the Nikuradse bottom roughness. The bottom stress under the influence of a turbulent current can be written as

$$\tau_c = \rho \kappa^2 \left(\ln \frac{30h}{k_s} - 1 \right)^{-2} U^2$$

with ρ the density of water (kg/m^3), κ the von-Karman constant equal to 0.4, h the water depth (m), k_s the Nikuradse bottom roughness (m) and U the depth-averaged current velocity (m/s). For the calculation of the Nikuradse bottom roughness k_s a distinction has to be made between the skin friction and the total friction. The skin friction is the roughness felt by the sediments at the bottom. In this model the expression of Engelund and Hansen (1967) is used to calculate the skin bottom roughness k_{ss}:

$$k_{ss} = 2.0 D_{65}$$

with D_{65} the grain size for which 65 % of the material has a smaller grain size (m). The total friction k_s on the other hand is the friction felt by the currents and is also influenced by the bottom load and by the bed forms. For the influence of the bottom load, the Grant and Madsen (1982) model is used, which calculates the bottom roughness under the influence of currents and waves:

$$k_{sb} = 160 K \left(\frac{\rho_s}{\rho} + C_m \right) D_{50} \theta_s \left[\left(\frac{\theta_s}{\theta_c} \right)^{0.5} - 0.7 \right]^2$$

with K a factor which accounts for the influence of the currents or the waves, ρ_s the density of the sediment (kg/m^3), C_m a form factor equal to 0.5 for spherical sediment particles, D_{50} the grain size for which 50 % of the material has a smaller grain size (m), θ_s the Shields parameter for the bottom stress at the bottom and θ_c the critical Shields parameter for the start of the bottom load transport. This Shields parameter is defined as:

$$\theta_s = \frac{\tau}{g(\rho_s - \rho) D_{50}}$$

For the critical Shields parameter for the initiation of the sediment transport, the curve of Shields (1936) is used. When the bottom stress exceeds the critical bottom stress for the initiation of transport, the total bottom roughness is enhanced by the bottom roughness induced by the bed load. The part of the total bottom friction, induced by the bed forms, is modelled using Grant and Madsen (1982): (1)

$$k_{sv} = 27.7 \eta \frac{\eta}{\lambda}$$

with η the height of the bed form (m) and λ the length of the bed form (m). The height and length of the bed forms are also calculated using empirical relations, proposed by Grant and Madsen (1982).

Finally, the model calculates the evolution of the bottom, using a continuity equation for the bottom sediments (Djenidi and Ronday, 1992):

$$\rho_s (1-p) \frac{\partial \xi}{\partial t} + \nabla \vec{Q} = 0 \qquad (2)$$

with p the porosity, ξ the position of the bottom in reference to the original position and with $\nabla \vec{Q}$ the divergence of the sediment transport vector.

The MU-SEDIM model was already used with success to model the sediment transport at the kink of the Westhinder bank (Deleu *et al.*, 2004) or to study the influence of the sand extraction on the sand transport and the stability of the Kwinte Bank (Van den Eynde *et al.*, 2009). More information on the numerical models used can be found in Van den Eynde *et al.* (2009).

4. Modelling of the morphodynamic changes of the Kwinte Bank for different bathymetries

4.1. Evolution of the bathymetry

The main goal of the paper is to use the developed numerical models to investigate the changes of the morphodynamic evolution under the influence of the changed bathymetry, due to sand and gravel extraction. These changes in the bathymetry over the last decade were studied in detail by Norro *et al.* (2003; 2006; 2009) and Norro and Ozer (2006).

Since the early 1980s, the monitoring of the bathymetric evolution of the Kwinte Bank was set up on the initiative of the authorities in charge of managing marine sand operations. Since 1988 sufficiently reliable single-beam sonar tracks were taken along linear transects perpendicular to the main axis of the Kwinte Bank. The quality of the data and the number of errors inherent in the measurements, including the tidal reduction and heave compensation, were carefully examined by Norro *et al.* (2003; 2006). Further, different profiles were discarded as not-reliable, due to false vertical registrations or badly navigated profiles. Norro *et al.* (2006) and Norro and Ozer (2006) used these bathymetric profiles to study the volumetric decline in the top of the Kwinte Bank. The top of the Kwinte Bank hereby is defined as the part of the bank above 15 m below Mean Low Low Water Spring (MLLWS). This level was used to allow a clear distinction between the sand bank and the surrounding area. The area of the top of the Kwinte Bank is presented in Figure 2. This evaluation showed that the volumetric decline of the top of the bank can be estimated at around 1.5 % per year during the period 1988-1999.

When at least 16 full profiles were available for a given cruise, a reconstruction of the bathymetry of the full sand bank was prepared (Norro *et al.*, 2003; 2009). A series of 13 Kwinte Bank bathymetries, covering the period 1991-1998, could be reconstructed. A table with the date of the campaigns and the campaign tags, used to define the different bathymetries, can be found in Table 1, together with the calculated volume of the top of the sand bank.

The method used for reconstruction was Kriging interpolation, a very flexible gridding method that incorporates anisotropy. Different anisotropy parameters were tested to obtain the most optimal results. The result of the last bathymetry, which could be reconstructed, was compared with the bathymetry, measured during five bathymetric surveys, executed by the Fund for Sand Extraction, using a Kongsberg Simrad EM1002 multibeam echosounder (Degrendele *et al.*, 2002). An mean error of 0.20 m ± 0.86 m was found. The differences were mainly observed in the northern part of the Kwinte Bank, characterised by the presence of numerous sand dunes. More information on the reconstruction of the different bathymetries and on the digital terrain model that was used for this purpose can be found in Norro *et al.* (2003; 2009).

Using the three-dimensional reconstructed bathymetries of the Kwinte Bank, the volumetric decrease of the top of the bank (above 15 below MLLWS) was estimated at around 1.36 million m^3 per year. This is in the same order of magnitude but higher than the estimated exploited volume in the same period, which is estimated by Norro *et al.* (2003) and Norro and Ozer (2006) at 0.9 million m^3 per year.

In Figure 7, the oldest bathymetry from campaign *Jul-1991* is presented. When comparing this bathymetry with the most recent bathymetry from campaign *Jun-1998* (Figure 2), one clearly sees that the Kwinte Bank was lowered over the years. The difference between these bathymetries is more clearly shown in

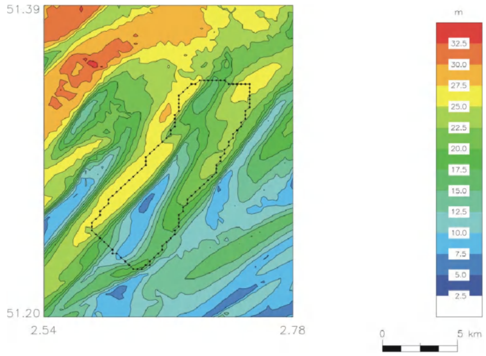

Figure 7: Detailed bathymetry of the Kwinte Bank, bathymetry *Jul-1991.*

Figure 8. One can remark that in the northern part of the Kwinte Bank, an area can be found, where the bathymetry is getting shallower. This is probably related to the presence and movements of the sand dunes in the area.

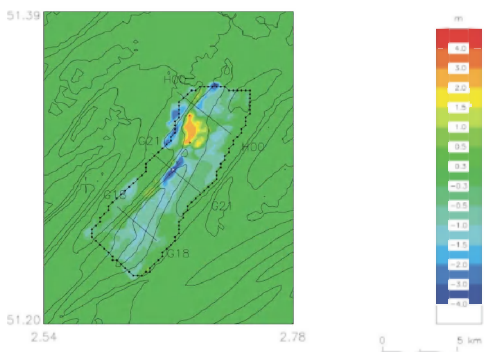

Figure 8: Difference between the bathymetry *Jun-1998* and the bathymetry *Jul-1991*. The location of the three profiles G18, G21 and H00 are indicated.

In Figure 9, the evolutions of three profiles over the Kwinte Bank are presented. The locations of the three profiles are indicated in Figure 8. Also here, the general erosion of the bank can be observed. Over the G18 and the H00 profiles, the lowering of the sand bank is clearly visible. At the G21 profile, the depression is apparent, which was caused by the extraction of sand.

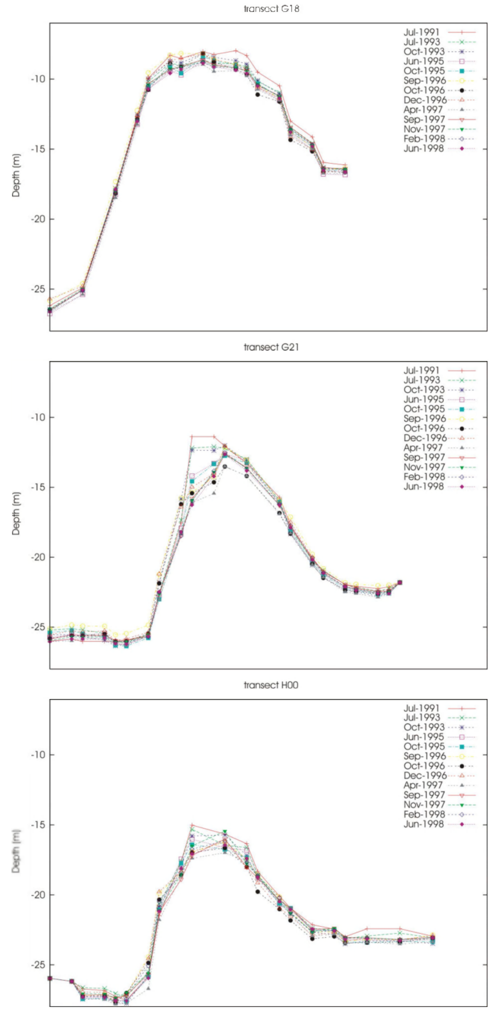

Figure 9: Three transects over the Kwinte Bank.

4.2. Sediment transport and morphological evolution

For the thirteen different bathymetries, the hydrodynamics and the sediment transport were calculated. In this study, the emphasis is on the influence of the different bathymetries on the sediment transport patterns and the morphological evolution. The effects of the atmospheric influences on the hydrodynamics and on the sediment transport were not accounted for here. The simulations were executed for a full neap-spring cycle, *i.e.*, from March 2nd, 2003 06h30 to March 17th, 2003 00h00, without and, for one simulation, with taking into account the influence of waves.

The sediment transport over the spring-neap cycle for the oldest bathymetry *Jul-1991* is shown in Figure 10. One can observe that the sediment transports on both sides of the bank are in opposite direction. On the gentle western side of the bank, the sand transport is to the northeast, while on the steep eastern side the sand transport is in the ebb direction, towards the southwest. At the eastern side, the transport directions on the top of the bank are veering to an almost perpendicular orientation with regard to the banks crest. This is in agreement with Caston and Stride (1970), which showed that the sediment transport directions on both sides of a tidal sand bank are opposite, caused by an amplification of the currents over each sand bank. The sediment transport clearly is the highest on the top of the sand bank, while the transports in the swales along the bank are much smaller.

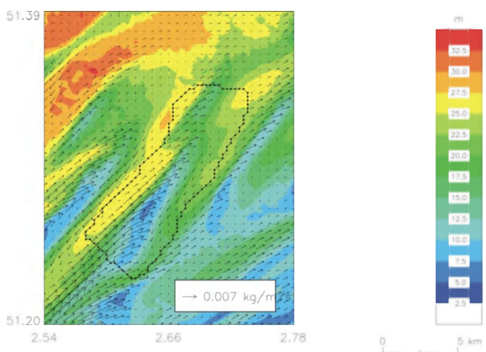

Figure 10: Calculated sediment transport vectors for a full spring-neap tidal cycle, using the *Jul-1991* bathymetry. One vector is shown for each calculated four vectors.

As shown in Van den Eynde *et al.* (2009), these results are in agreement with observations of sediment transport patterns on the Kwinte Bank. Roche *et al.* (2004) showed similar patterns in sediment transport pathways, derived on the basis of the observed dune asymmetries. Lanckneus *et al.* (1994; 2001) showed that these dune asymmetries can be used to derive sediment transport directions. Bellec *et al.* (2009) and Van Lancker *et al.* (2009a) reported similar sediment transport patterns. Also other numerical studies showed similar sediment transport patterns (*e.g.*, Brière *et al.*, 2009).

The erosion and sedimentation patterns, correlating with the calculated sediment transport, are shown in Figure 11. The figure shows that in calm weather conditions, *i.e.*, without taking into account the atmospheric conditions and the waves, the sediment transport tends to make the sand bank shallower. This is in agreement with results obtained in the framework of the RESECUSED project (De Moor and Lanckneus, 1993), where it is shown that in quiet weather conditions, the upslope movement of sand under the influence of near-bed currents cause an up piling of sand, while in storm conditions, the down slope dispersion of sand results in a top volume decrease.

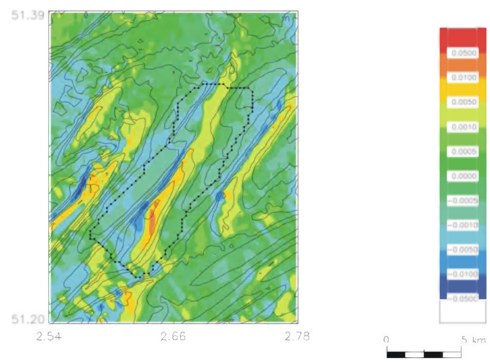

Figure 11: Evolution of the bottom (in m), calculated by the sediment transport model MU-SEDIM, for the *Jul-1991* bathymetry over a full spring-neap tidal cycle.

4.3. Influence of the bathymetrical changes on the erosion/sedimentation patterns

To investigate the overall influence of the changes in the bathymetry of the Kwinte Bank on the erosion and sedimentation, the total amount of modelled eroded and deposited material for the top of the Kwinte Bank was calculated for the different bathymetries. In Figure 12, the evolution is shown of the erosion and deposition, extrapolated from the modelled period of 14 days to a full year. The deposition is almost constant at around 100 000 m³ per year. The modelled erosion decreases from -457 000 m³ for bathymetry *Jul-1991* to -387 000 m³ for bathymetry *Jun-1998*. This results in a deposition/erosion balance, decreasing from -344 000 m³ in 1991 to -269 000 m³ in 1998. One has to recall that when calculating sediment transport, using total load sediment transport formulae, still large uncertainties exist. Soulsby (1997) mentions that, in the sea, the total sediment transport formulae give predictions within a factor of 5 in 70 % of the (non-calibrated) cases. The exact values of the eroded volume therefore have to be considered with the necessary precautions. However, the fact that the modelled erosion has the same order of magnitude as the difference between the calculated volumetric decrease of the top of the sandbank (1 360 000 m³ per year) and the estimated extracted volume (900 000 m³ per year), which is 460 000 m³ per year, is giving some confidence in the model results.

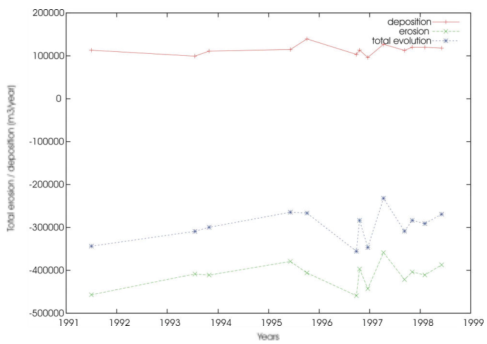

Figure 12: The evolution of the erosion/deposition of the Kwinte Bank area for the different bathymetries.

Further, one additional simulation was executed, taking into account the wave effects. For the same period, the significant wave height was calculated, using the MU-WAVE model. As Giardino *et al.* (2009) showed, waves can have important effects on the sediment transport, as well on the magnitude of the sediment transport as on the direction of the sediment transport. In this case, the bottom stress was calculated taking into account the combined effect of currents and waves, and the total load formulae of Ackers and White was adapted, using the modifications, proposed by Swart (1976; 1977, in: Sleath, 1984), to take the wave effects into account. In this case, a higher total erosion of the top of the Kwinte Bank was calculated of 527 000 m³ per year. This value is even closer to the natural erosion, calculated from the volumetric analysis of Norro *et al.* (2006) and Norro and Ozer (2006). Here again, however, one must use these results with the necessary precautions. It is clear that the sediment transport is highly variable and that the waves can have important effects. It is therefore difficult to extrapolate the results for a period of 14 days to a yearly value.

When comparing the number of grid points where erosion occurs and the number of grid points where accretion occurs, one observes that almost 3.5 times more grid cells are found where erosion occurs, than grid cells with accretion.

Finally, one could observe that the erosion seems to decrease over the years (Figure 12). However, taking into account the uncertainties in the model results and the restricted number of results, this trend is not significant, and no conclusive statements can be made on the evolution of the erosion of the sand bank, due to the extraction of the sand on the Kwinte Bank.

5. Conclusions

The goal of the present paper is to get an indication of the influence of the changing bathymetry, due to extraction of sand and gravel, on the stability of the sand bank. Norro *et al.* (2006) and Norro and Ozer (2006) showed by an analysis of the bathymetric profiles over 21 cross-sections of the Kwinte Bank over a period 1991 to 1999, that a decline in the volume of the bank is clearly highlighted, with a maximum around the transects where the sand extraction operations are concentrated. They found an average decline of approximately 1.5 % per year, which indicated a decrease of 1.36 million m³ per year of the volume of the bank above the reference depth of 15 m below MLLWS. Further Norro *et al.* (2003, 2009) studied the decline of the volume of the reconstructed three-dimensional bathymetries, where a similar decline of the top of the sand bank was found. On the other hand, the amount of sand extracted in the area of interested in the same period was estimated by Norro and Ozer (2006) at about 0.9 million m³ per year. These values are in the same order of magnitude, with the amount of extracted sand being smaller. Therefore, they concluded that the sand extraction indeed has an impact on the volume of the Kwinte Bank and that the fact that the estimated impact is greater than the estimated workload seems to indicate that the dynamic balance of the bank even might be perturbated.

In the present paper, the sediment transport and the erosion and sedimentation on the Kwinte Bank were calculated with a numerical model, using the series of bathymetries, which were reconstructed from the bathymetric profiles. The calculations show a clockwise sediment transport, with sediment transport towards the northeast on the steep western side of the sand bank and to the southwest on its gently sloping eastern side. This pattern is in general agreement with the observations (*e.g.*, Van Lancker *et al.*, 2009a).

From the simulations with a sediment transport model, one can conclude that the difference between the observed volumetric decline of the top of the Kwinte Bank and the estimated sand extraction, probably can be addressed to natural erosion of the sand bank. Indeed, the numerical model shows a natural erosion of the sand bank of the same order of magnitude, certainly when the influence of waves are taken into account. This natural erosion of the sand banks in the Belgian coastal waters was also put forward by De Moor (2002). In that paper, De Moor mentions that all Flemish Banks are subject to erosion during the period 1985 – 1995. On the Kwinte Bank the erosion is the largest: near the kink in the Kwinte Bank (near the Central Depression) values are measured of 12 cm/year to 25 cm/year. Also over the rest of the Kwinte Bank values are found around 6 cm/year. On the Buitenratel Bank (Figure 1), erosion was measured of 2 cm/year to 8 cm/year. On the Middelkerke Bank, the erosion seems smaller, but also there, at some places, erosion is measured of 7 cm/year.

This natural erosion in also agreement with the results of Degrendele *et al.* (2009), who showed that, at least in the short-term, after the cessation of the extraction in the Central Depression, still some small erosion occurred in the Central Depression of about 12 cm during the period March 2003 to June 2005. They showed that this erosion was correlated with similar erosion, observed in a reference area on the nearby Middelkerke Bank (Figure 1), a bank which was not subject to marine aggregates extraction. Also other information showed that the Central Depression was still subject to erosion (Van Lancker *et al.*, 2009a), although there are also some indications that on a longer period, regeneration could be possible (Van Lancker *et al.*, 2009a).

The evolution of the natural erosion, as calculated by the numerical model for the different bathymetries, doesn't show a clear trend. This indicates that the extraction of the sand, although obviously having an impact on the volume of the sand bank, doesn't significantly influences the sediment transport patterns and the natural erosion of the sand bank as such.

The fact that sand bank is subject to natural erosion, as shown by the numerical simulations and the observations, implies that the sand bank can not recover from the volume decline, caused by the sand extraction. This raises the question of the sustainability with regard to the extraction of marine aggregates. In Wellmer and Becker-Platen (2002), guidelines on sustainable exploitation of renewable resources were described, which state that 'the rate of consumption should not exceed the rate at which they are regenerated' (Van Lancker *et al.*, 2009a). Since the measurements and the numerical model results indicate that the extraction is having important effects on the sand bank, which already is subject to natural erosion, more monitoring and research could be necessary. It suggests that the authority should define maximum exploitable quota preventing any irreversible damage.

Acknowledgments

This research was supported by the financial recourses from the fees paid by the holders of licenses for marine sand exploitation issued by the Belgian authorities. The study frames into the research objectives of the project QUEST4D "Quantification of Erosion and Sedimentation patterns to Trace the natural versus anthropogenic sediment dynamics", supported by the Belgian Federal Office and the project SUMARE "Survey of Marine Resources", partly funded by the Information Society Technologies (IST) Programme of the European Union. The captain and the crew of the R.V. *Belgica* are thanked for their flexibility and assistance during the campaigns. The anonymous reviewer is thanked for the constructive comments, which improved the quality of the paper.

References

Ackers, P. and W.R. White, 1973. Sediment transport: new approach and analysis. Proceedings of the ASCE Journal of Hydraulics Division 99 (HY11), 2041-2060.

Bellec, V., V. Van Lancker, K. Degrendele, M. Roche and S. Le Bot. Geo-environmental characterization of the Kwinte Bank. Journal of Coastal Research, Special Issue Eumarsand, in press.

Bidlot, J.R., F. Ovidio and D. Van den Eynde, 1995. Validation and improvement of the quality of the operational wave model MU-WAVE by the use of ERS-1 satellite data. Report MUMM/T3/AR04, Final Report, Management Unit of the North Sea Mathematical Models, Brussels, 53 pp.

Brière, C., P. Roos and E. Garel, 2009. Modeling the morphodynamic effects of sand extraction from the Kwinte Bank. Journal of Coastal Research, Special Issue Eumarsand, in press.

Caston, V.N.D. and A.H. Stride, 1970. Tidal sand movement between some linear sand banks in the North Sea off northeast Norfolk. Marine Geology, 9, M38-M42.

Degrendele, K., M. Roche and P. Schotte, 2002. Synthesis of data acquired from November 1999 to April 2001 concerning the extraction activities on the Kwinte Bank (in french). Technical Report, Fund for Sand Extraction, Ministry of Economic Affairs, 23 pp.

Degrendele, K., M. Roche, P. Schotte, V. Van Lancker, V. Bellec and W. Bonne, 2009. Morphological evolution of the Kwinte Bank central depression before and after cessation of aggregate extraction. Journal of Coastal Research, Special Issue Eumarsand, in press.

Deleu, S., V. Van Lancker, D. Van den Eynde, G. Moerkerke, 2004. Morphodynamic evolution of the kink of an offshore tidal sandbank: the Westhinder Bank (Southern North Sea). Continental Shelf Research, 24, 1587-1610.

Djenidi, S. and F. Ronday, 1992. Dynamique sédimentaire en mer à marée. In : Etude du plateau continental nord-ouest Européen : Structure et mouvements verticauxs. Institut de recherches marines et d'interactions air-mer. Université de Liège, 53-61.

De Moor, G., 2002. Evaluation of sea-floor sediment dynamics in the Flemish Banks (southern North Sea) between 1985 and 1995. [Evalution de la morphodynamique sous-marine en Mer du Nord méridionale au cours de la période 1985-1995.] Géomorphologie: relief, processus, environnement, 8, 179-194.

De Moor, G. and J. Lanckneus (eds.), 1993. Sediment Mobility and Morphodynamics of the Middelkerke Bank. Finale Report MAST Project-0025-C, Relation between Seafloor Currents and Sediment Mobility in the Southern North Sea, Universiteit Gent, 244 pp.

Engelund, F.A. and E. Hansen, 1967. A monograph on sediment transport in alluvial streams. Teknikal Forlag, Copenhagen.

Giardino, A., D. Van den Eynde and J. Monbaliu, 2009. Wave Effects on the Morphodynamic Evolution of an Offshore Sandbank. Journal Journal of Coastal Research, Special Issue Eumarsand, in press.

Grant, W.D. and O.S. Madsen, 1982. Movable bed roughness in unsteady oscillatory flow. Journal of Geophysical Research, 87, 469-481.

Günther, H. and W. Rosenthal, 1985. The hybrid parametrical (HYPAS) wave model. Ocean wave modelling, Swamp group. Plenum Press, New York, 211-214.

ICES, 2005. Report of the Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem (WGEXT), San Sebastian, 5-8 April 2005. ICES WGEXT Report 2005, ICES Marine Habitat Committee, ICES CM 2005/E:06, 102 pp.

Lanckneus, J., G. De Moor and A. Stolk, 1994. Environmental setting, morphology and volumetric evolution of the Middelkerke Bank (Southern North Sea). Marine Geology, 121, 1-21.

Lanckneus, J., V. Van Lancker, G. Moerkerke, D. Van den Eynde, M. Fettweis, M. De Batist and P. Jacobs, 2001. Investigation of the natural sand transport on the Belgian Continental Shelf (BUDGET). Final Report. Federal Office for Scientific, Technical and Cultural Affairs (OSTC), 104 pp. + 87 pp.

Luyten, P.J., J.E. Jones, R. Proctor, A. Tabor, P. Tett and K. Wild-Allen, 1999. COHERENS: A Coupled Hydrodynamical-Ecological Model for Regional and Shelf Seas: User Documentation. Management Unit of the North Sea Mathematical Models, Brussels, 914 pp.

Norro, A. and J. Ozer, 2006. Long term volumetric evolution of an exploited sandbank. Case study on the coastal Belgian North Sea Kwintebank. Journal of Coastal Research, SI 39 (Proceedings of the 8th International Coastal Symposium), Itajai, SC, Brazil, 796-800.

Norro, A., G. Pichot, J. Ozer, B. Lauwaert and D. Van den Eynde, 2003. SUMARE D.5. Data Assimilation, a. Sandbank Application. Technical Report, Management Unit of the

North Sea Mathematical Models, Brussels, 36 pp.

Norro, A., G. Pichot, V. Pison and J. Ozer, 2006. A bi-dimensional approach to assessing the volumetric evolution of an exploited sandbank. ICES Journal of Marine Science, 63, 176-186.

Norro, A., F. Francken and J. Ozer, 2009. Volumetric evolution of an exploited sandbank using three-dimensional reconstruction method based on sequential bathymetric profiles. The Belgian Kwintebank case (southern North Sea). Submitted to Netherlands Journal of Geosciences.

Ovidio, F., J.R. Bidlot, D. Van den Eynde, W. Luo and J. Monbaliu, 1994. Validation of the second generation wave forecasting model MU-WAVE: comparison with ERS-1, buoy data and WAM forecasts. In: Proceedings of the First ERS-1 Pilot Project Workshop, Toledo, Spain, 22-24 June 1994, 21-28.

Pison, V. and J. Ozer, 2003. Operational products and services for Belgian coastal waters. In: Dahlin, H., N.C. Flemming, K. Nittis and S.E. Peterson (eds.), Building the European Capacity in Operational Oceanography. Proceedings of the Third International Conference on EuroGOOS. Elsevier Oceanography Series, 69, 503-509.

Roche, M., K. Degrendele and P. Schotte, 2004. Introduction to the Kwinte Bank from a geomorphological perspective. Fund for Sand Extraction, Ministry of Economic Affairs. Presentation on the SPEEK Workshop, Gent.

Shields, A., 1936. Anwendung der Ähnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung. Mitt. Preuss. Versuchsanstalt für Wasserbau und Schiffbau, Berlin, 26 pp.

Sleath, J.F.A., 1984. Sea Bed Mechanics, Wiley-Interscience, New York, 335 pp.

Soulsby, R.L., 1997. Dynamics of Marine Sands, London, Thomas Telford, 272 pp.

Swart, D.H., 1976. Coastal sediment transport. Computation of longshore transport. Report R968 (1), Delft Hydraulics Laboratory, The Netherlands, 61 pp.

Swart, D.H., 1977. Weighted value of depth of initiation of movement. Report NR10, Stellenbosch, South Africa.

Van den Eynde, D., 1992. mu-WAVE: An operational wave forecasting system for the Belgian coast. In: Proceedings of the 3rd International Workshop on Wave Hindcasting and Forecasting, May 19-22 1992, Montréal, Canada, 313-324.

Van den Eynde, D., A. Giardino, J. Portilla, M. Fettweis, F. Francken and J. Monbaliu, 2009. Modelling the effects of sand extraction, on sediment transport due to tides, on the Kwinte Bank. Journal of Coastal Research, Special Issue Eumarsand, in press.

Van Lancker, V., S. Deleu, V. Bellec, S. Le Bot, E. Verfaillie, M. Fettweis, D. Van den Eynde, F. Francken, V. Pison, S. Wartel, J. Monbaliu, J. Portilla, J. Lanckneus, G. Moerkerke and S. Degraer, 2004. Management, research and budgeting of aggregates in shelf seas related to end-users (Marebasse). Scientif Report, Year 2. Federal Office of Scientific, Technical and Cultural Affairs (OSTC), 144 pp.

Van Lancker, V.R.M., W. Bonne, E. Garel, K. Degrendele, M. Roche, D. Van den Eynde, VL Bellec, C. Brière, M.B. Collins and A.F. Velgrakis, 2009a. Recommendations for the sustainable exploitation of tidal sandbanks. Journal of Coastal Research, Special Issue Eumarsand, in press.

Van Lancker, V.R.M., W. Bonne, A.F. Velegrakis and M.B. Collins, 2009b. Aggregate extraction from tidal sandbanks: is dredging with nature an option? Introduction. Journal of Coastal Research, Special Issue Eumarsand, in press.

Wellmer, F. and J. Becken-Platen, 2002. Sustainable development and the exploitation of mineral and energy resources: a review. International Journal of Earth Sciences, 91, 5, 723-745.

Table 1: Dates and names of the campaigns and bathymetries, together with the volume of the top of the bank, calculated from the three-dimensional reconstruction of the bank.

Name of bathymetry	Date of campaign	Volume of bank
Jul-1991	02 07 1991	91907108
Jul-1993	16 07 1993	89928058
Oct-1993	27 10 1993	88559472
Jun-1995	06 06 1995	83413305
Oct-1005	04 10 1995	87486111
Sep-1996	25 09 1996	96105147
Oct-1996	18 10 1996	83692511
Dec-1996	17 12 1996	87682364
Apr-1997	09 04 1997	80897573
Sep-1997	08 09 1997	85560320
Nov-1997	03 11 1997	83901295
Feb-1998	02 02 1998	85005069
Jun-1998	03 06 1998	81947029